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Half Pins Stress Shielding Interaction Behavior at Implant-Bone Interface

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Abstract: This paper presents the fixation stability of tapered conical half-pin and trocar-tip tapered half-pin due to self-pin loosening failure of uniaxial external fixator for femur diaphysis cortical bone. Clinical failure of external fixator is caused by the stress interaction between assembled pin, ring, rods and locking devices. Screw pins that used to hold the fixation stability are reported to fail due to screw loosening. This study aims to investigate the pin-bone stress interaction mechanism between tapered conical (TC) half-pin and trocar-tip tapered (TTT) half-pin based on stress transfer parameter (STP). Finite element (FE) analysis has been conducted and STP algorithm has been executed for TC and TTT half pin configuration. The effect of pin's types and materials on the load sharing with surrounding bone resorption were analysed. TC and TTT half pin models were analysed using four types of materials (titanium alloy Ti-6Al-4V, stainless steel 316L, magnesium alloy and carbon fiber) to determine the von-Mises stress and stress-strain shielding. It is found that the pins were yielded at the thread of pin near to hard-soft tissue interface which is agreed with the reported clinical screw implant fracture. A high value of von-Mises for TTT made by stainless steel shows that the pin material gives a good mechanical stimulus but TTT made by magnesium alloy possess the highest STP between the pin and the bone and at the same time increase the level of stability in order to starts the bone remodelling process.

Keywords: fixation stability, screw loosening, stress transfer parameter

1. Introduction

An external fixation device is a surgical treatment used to keep fractured bones stabilized and in alignment. It used to be adjusted externally to ensure the bones (e.g. femoral shaft and distal femur) remain in an optimal position during the healing process. There are also three main fractures occur at femoral shaft which are simple fracture, wedge fractures and complex fractures [1]. After implantation, in healing period, the external fixator (EF) may failed and patience may experience pain due to the pin screws loosening or tightening and fracture of the external fixation that hold the bone together to stabilize the broken bone [2,3]. A newly design of uniaxial EF has been introduced by Hospital Universiti Kebangsaan Malaysia (HUKM) and Universiti Malaysia Perlis (UniMAP) as an universal fixator for bone fracture treatments was used for this research. Under three-point and four-point bending condition, the fixation stability is reduced through the mechanism of loosening or tightening and finally caused the transverse fracture. This study aims to investigate the fixation stability of tapered conical (TC) half-pin and trocar-tip tapered (TTT) half-pin due to self-pin loosening based on stress interaction and stress transfer parameter (STP) method.

2. Finite Element Modeling

The geometrical model of EF was designed in SolidWorks 2014. The length of an adult femur bone is 48 cm while the diameter of the cortical bone is 2.34 cm. The thickness of the cortical bone at the femoral shaft is 3 mm [6]. There are 4 screws attached to the femur bone where the distance of each pins was set to be 62 mm, 162 mm and 62 mm to each other. However, the study considered the half pin-bone interaction in 2-dimensional only. FE analysis are conducted in ANSYS Mechanical APDL and the meshing process is based on [5]. The geometries of both TC and TTT of the half pins were taken from the actual Synthes orthopedic pins. The assembled bone and fixator will then undergo FE analysis to identify the von-Mises stress-strain and deformation of the model. Fig. 1 shows the location of stresses for the calculation of stress transfer parameter (STP) along the interaction. After the simulation, the STP ratio of stresses between pin and bone are calculated by using Eq. (1).

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$$\mathrm{STP} = \sum_{i=j=2}^{i=j=N} \frac{\sigma_{bi}}{\sigma_{tj}} \quad (1)$$

From the equations, σ_{bi} shows the stress transfer from bone, σ_{tj} is stress transfer from thread.

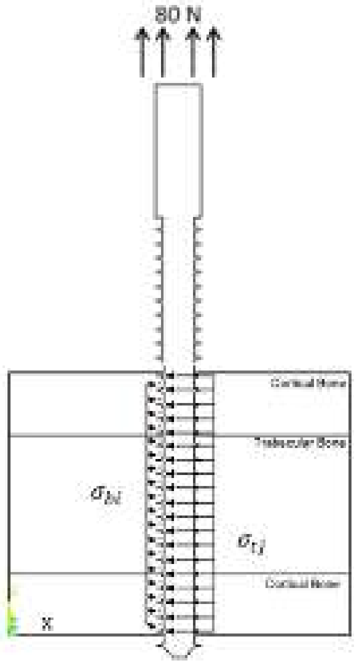

Fig. 1 Boundary condition of two dimensional pin-bone interaction

STP is used to analyze the stress shielding between the interaction of the half-pin and bone besides it. Fig. 2 (a) and (b) show the meshing scheme of 2-D FE model for TC and TTT half-pins where the element type used in this simulation was plane 183 solid elements in plain strain condition. The meshing element was set as 8-node quadrilateral where a constant pull out load of 80 N was applied during the simulation to simulate tightening [7]. The material properties are assumed to be homogeneous, isotropic and linear elastic.

Table 1 External fixator-bone assembly material properties

Material	Elastic modulus (GPa)	Poisson's Ratio
Cortical bone	17.0	0.33
Cancelous bone	1.10	0.35
Titanium alloy (Ti-6Al-4V)	120.0	0.32
Stainless Steel 316L	193.0	0.31
Magnesium Alloy	45.0	0.35
Carbon Fiber	113.0	0.32

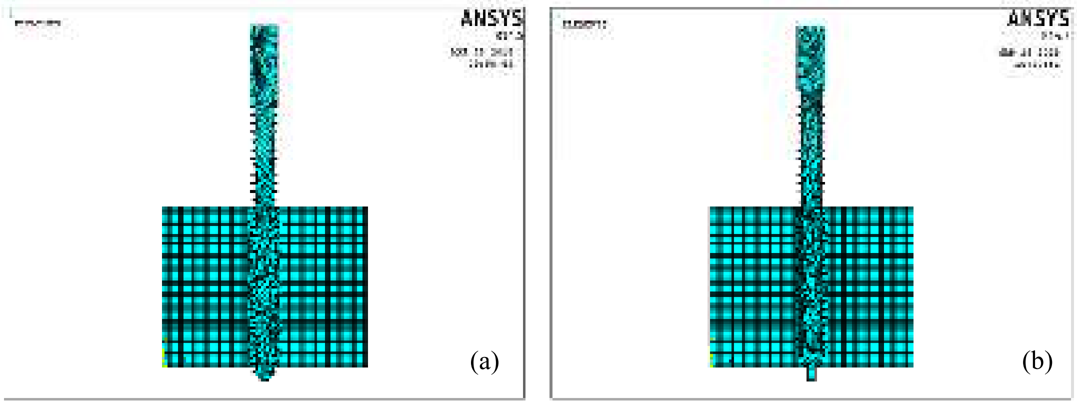

Fig. 2 (a) Meshing of tapered conical half-pin (b) Meshing of trocar-tip tapered half-pin

3. Results and Discussion

Table 2 tabulated the von-Mises stress comparison between TC and TTT half-pin configuration for titanium alloy Ti-6Al-4V, stainless steel 316L, magnesium alloy and carbon fiber. In comparison, TTT half pin made by stainless steel has the highest stress compared to the others followed by titanium alloy, carbon fiber and magnesium alloy. Moreover, to locate the critical yield area under loading condition, Figures 3 – 6 show the von-Mises stress contour where the highest stress of each interactions occur at second last threads of the pins. It is clearly observed that the critical stress seems to yield at the thread location. Similarly, the same trend of highest von-Mises stress can be seen in the TC half-pin.

Table 2 Maximum von-Mises stress

Type of half-pin	Maximum von-Mises stress			
	Titanium Alloy	Stainless Steel	Magnesium Alloy	Carbon Fiber
Tapered conical (TC)	1347.90	1699.09	1005.44	1327.01
Trocar-tip tapered (TTT)	1416.81	1889.87	836.27	1361.14

Stainless steel has the highest stiffness and yield strength which lead to brittle fracture rather than ductile fracture. This is the main reason of reported clinical fracture of broken pin screws. The results also revealed the possibility of cortical bone fracture. TC half-pin screw seems to have high tendency to cause the cortical bone fracture for all TC half-pin material. Magnesium alloy is observed to significantly experience the highest stress yielding as shown in Fig. 5(a). Despite the material stiffness, the yielding is due to the diameter of TC half-pin and the geometrical thread may provide higher STP to the surrounding bone.

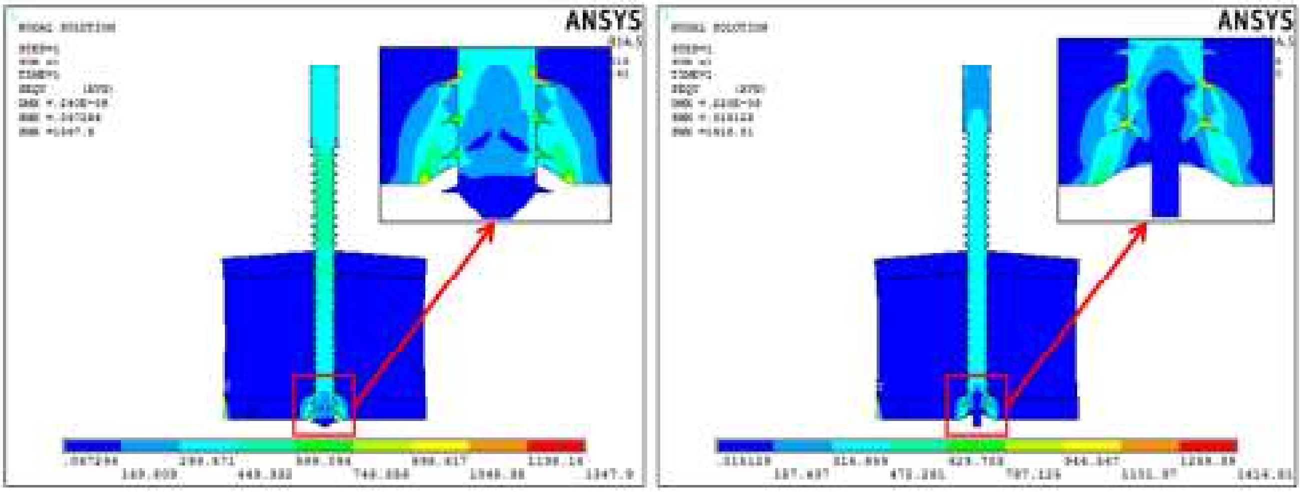

Fig. 3 (a) Highest stress of TC half-pin for titanium alloy (b) Highest stress of TTT half-pin for titanium alloy

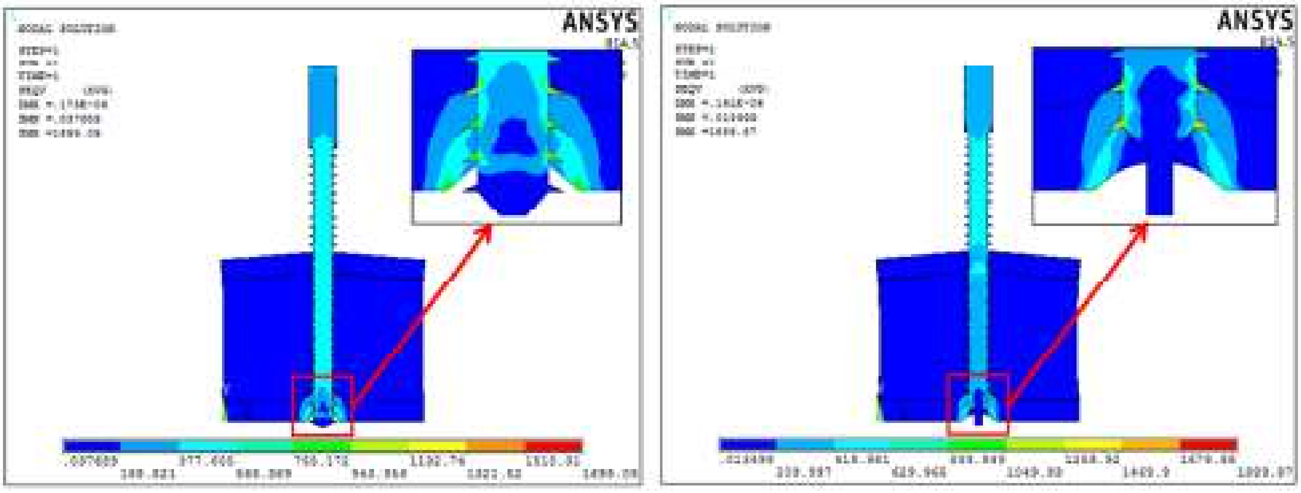

Fig. 4 (a) Highest stress of TC half-pin for stainless steel (b) Highest stress of TTC half-pin for stainless steel

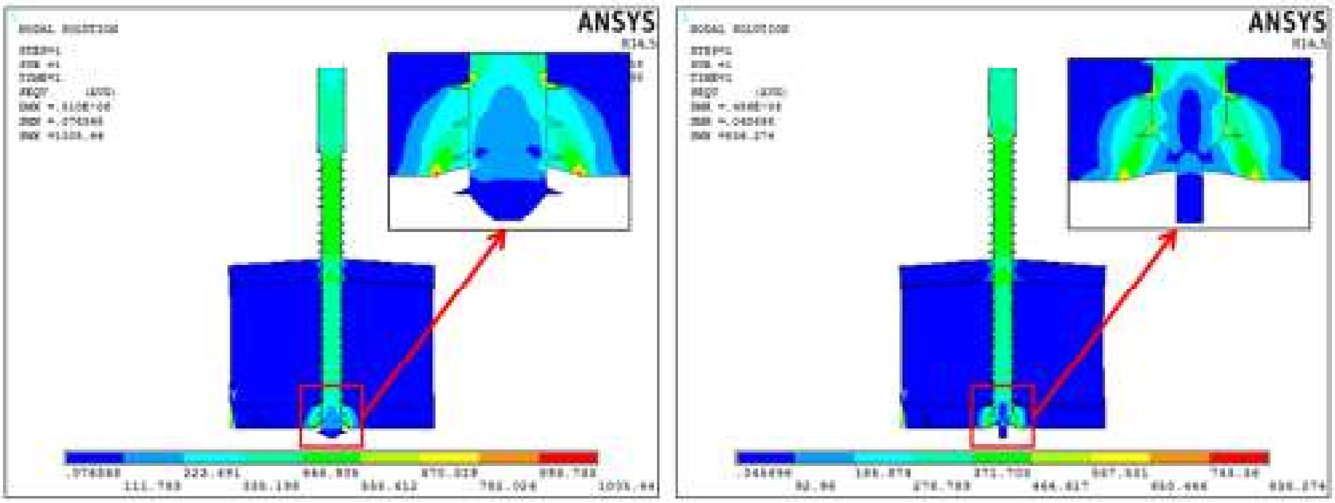

Fig. 5 (a) Highest stress of TC half-pin for magnesium alloy (b) Highest stress of TTC half-pin for magnesium alloy

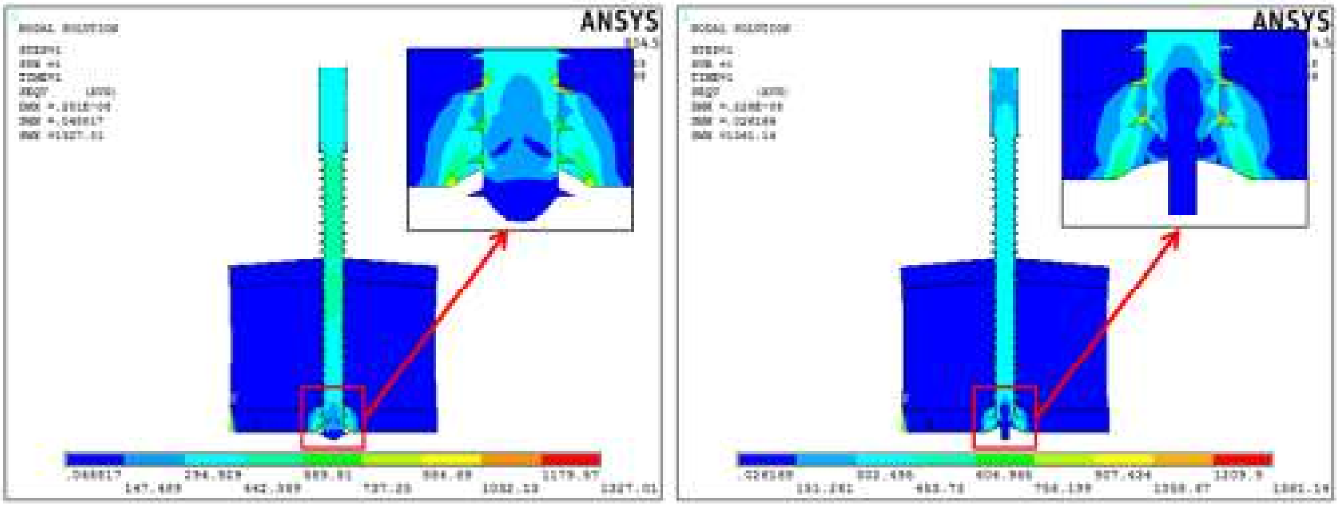

Fig 6 (a) Highest stress of TC half-pin for carbon fiber (b) Highest stress of TTT half-pin for carbon fiber.

Fig. 7 shows that magnesium alloy supplied the highest STP for both types of pins. In relation von-Mises stress in Fig. 3, the material that has the lowest maximum von-Mises has the highest value of STP.

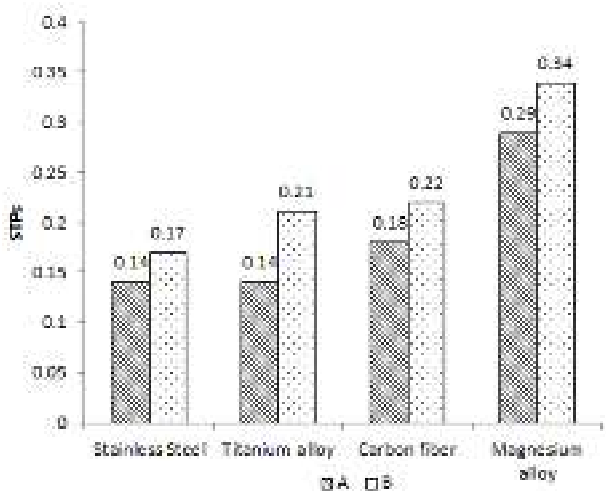

Fig. 7 Effect of pins materials on average STPs

A high value of STP shows that the material of the pin gives a good mechanical stimulus where the stress transfer is higher between the pin and the bone and at the same time increase the level of stability in order to starts the bone remodelling process. As shown in Fig. 7, stainless steel gives the largest stress shielding followed by carbon fiber and titanium alloy. The increment of the STP value of titanium alloy is 24% while stainless steel is 21%. As for magnesium alloy and carbon fiber, the value of STP increases by 17% and 22%, respectively. Stress shielding also depends on the structure of the implant. The STP changes with different types of pins where TTT half pin (pin B) have a higher value of STP compared to the TC half-pin (pin A). The values of STP for titanium alloy and carbon fiber are almost similar where from the figure the values for both STPs are almost overlapping on each other. The value of elastic modulus influenced the value of STP where the lowest modulus gives the highest STP. Percentage difference between the TTT half pin and TC half pin for each of the materials falls between 17 to 23%. These results corresponds to a study made by A. Gefen [8] where all of the STP values

4. Summary

The ability to transfer stress from pin-thread to bone σ_{tj} and bone to pin-thread σ_{bi} with equal distribution between threads and the surrounding bone tissue is an important factor in determine the performance of pins designs in term of biomechanical compatibility and fixation stability [10]. Therefore, it can be observed that the TC and TTT half-pin stainless steel has the highest stress interaction compared to the other materials. However, it's incapable to provide sufficient STPs for better bone healing compared to other TC and TTT half-pin material. The result obtained based on the stress transfer STPs. The von-Mises stress analysis indicated the highest stress at the location of second last thread at soft-hard tissue interface, and STP of TTT half-pin made by magnesium alloy gives the most optimum value of STP and provide the optimum bone healing and osseointegration process.

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